ORBITER TILE IMPACT TESTING

Final Report

for

SwRI Project No. 18-7503-005

Prepared for

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Houston, Texas

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1.0 INTRODUCTION

This final report presents the results of a study in which Space Shuttle Orbiter high temperature reusable surface insulation (HRSI) tiles were impacted with NCFI (North Carolina Foam Insulation) 24-124 foam insulation. The objectives of the study were to: (1) evaluate the tile damage capability of NCFI 24-124 foam fired at various angles of attack, velocities and sizes; (2) confirm the current data base established from previous tile impact tests, and (3) to obtain high speed photographic records of the foam impact. Background information on this subject is discussed in the following section. A discussion of the test equipment, test matrix and procedures is given in Section 3.0. Tabulated test results are presented in Section 4.0 with further discussions given in Section 5.0.

2.0 BACKGROUND

Originally the external tank on the orbiter was coated with a sprayed on foam insulation material known as SOFI. Due to environmental concerns, the SOFI material was replaced with NCFI 24-124 foam insulation. The first orbiter flight to have the NCFI 24-124 foam insulation was Flight STS-87. During this flight, the external tank of the Orbiter experienced a significant loss of thermal protection material from the intertank thrust panel region. This problem did not occur with the previously used SOFI insulation material. The NCFI 24-124 foam materials lost from the thrust panels have been implicated as causing significant damage to the HRSI tiles on the lower surface of the Orbiter. Subsequent modifications to the intertank thermal protection material for future STS Flights -89, 90 and 91 did show improvements; however, these improvements did not eliminate the problem. This project was conducted to characterize the damage inflicted on HRSI tiles by the NCFI 24-124 foam insulation material and to provide information to NASA that could be used to correlate to observed flight damage.

3.0 EXPERIMENTAL SETUP AND TEST PROCEDURES

The following section describes the equipment used to conduct the impact tests, the Orbiter HRSI tile targets, the NCFI 24-124 foam projectiles, test procedures, and the test matrix.

3.1 Test Facility and Equipment Description

All testing was completed at Southwest Research Institute's Ballistics and Explosive Range located in San Antonio, Texas.

3.1.1 Compressed Gas Gun

The small compressed gas gun (Figure No. 1) was used to launch the foam projectiles at the Orbiter HRSI tile targets. High pressure helium gas was chosen as the driver gas to propel the foam projectiles to the desired velocities. Originally it was thought that the various sizes of foam could best be launched using a sabot package. However, early on in the program, it became apparent that the only feasible way to launch the fragile foam projectiles without breaking them up was to build custom barrels that had a bore dimension which matched the cross section of each projectile size. Three barrels were fabricated including a 1.0" x 1.0" square bore barrel for the 1.0" x 1.0" x 1.0" and 1.0" x 1.0" x 3.0" projectiles, a 3/8" diameter barrel for the 3/8" dia. x 1.0" and 3.0" long projectiles, and a 0.89" x 0.25" rectangular barrel for the 0.89" x 0.89" x 0.25" projectile. The 1.0" x 1.0" and the 0.89" x 0.25" square barrels were 11 feet long. The 3/8" barrel was 8 feet long. All three barrels were fabricated with a flange that mated to the pressure chamber of the small gas gun.

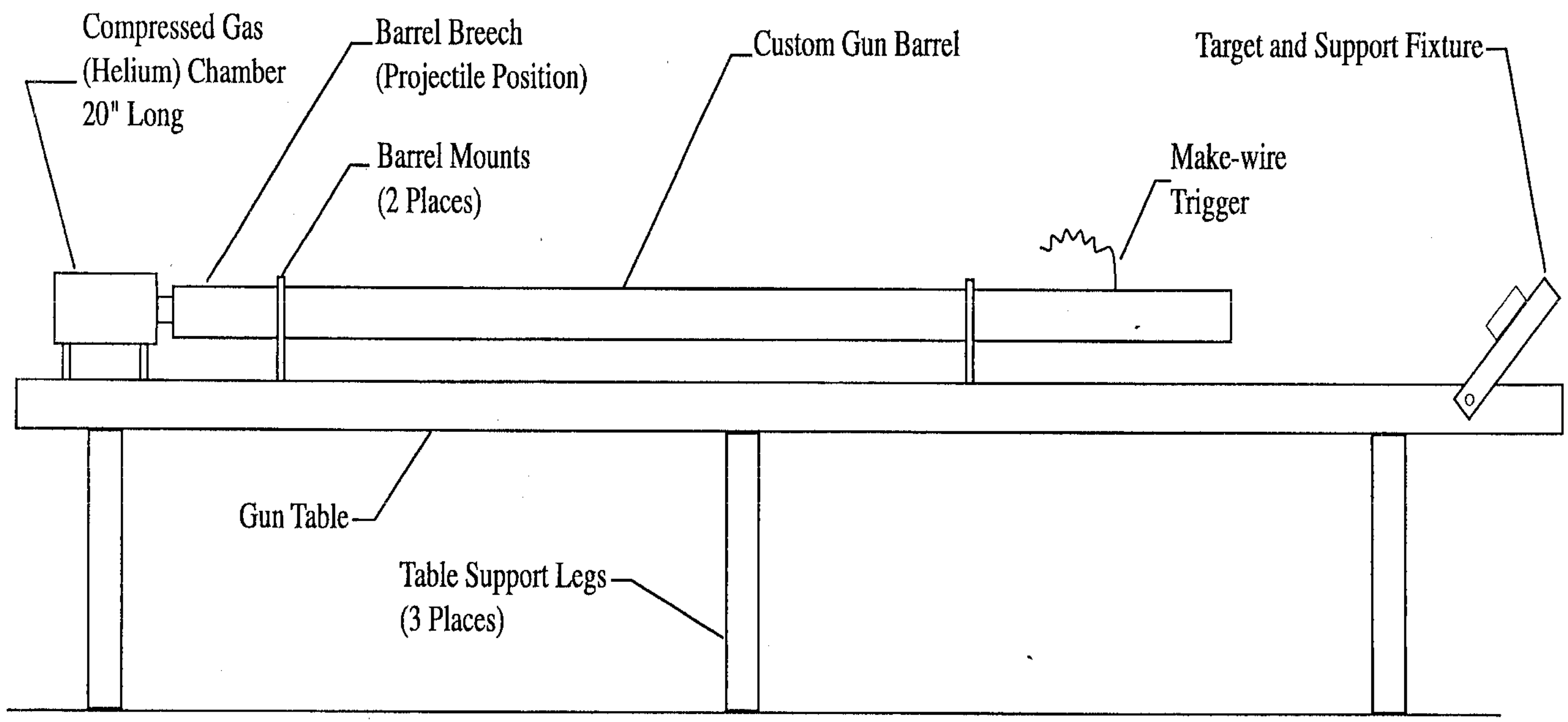


Figure 1: Compressed Gas Gun

3.1.2 Target Fixture

A rigid target fixture (Figure No. 2) was fabricated from ¼" thick steel plate. The target fixture was clamped rigidly to the gun support structure. The tile targets were fastened to the target fixture using fiber-reinforced tape as requested by the sponsor. The target fixture was easily rotated to acquire the necessary impact incidence angle.

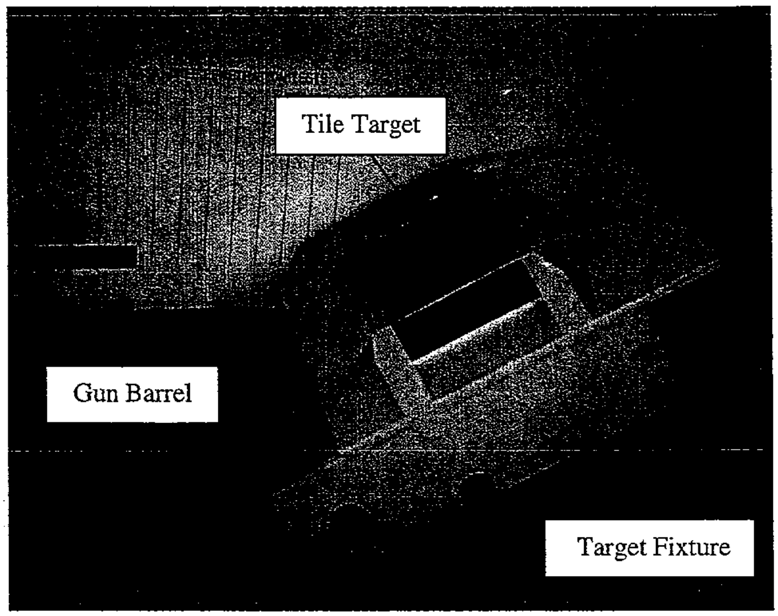


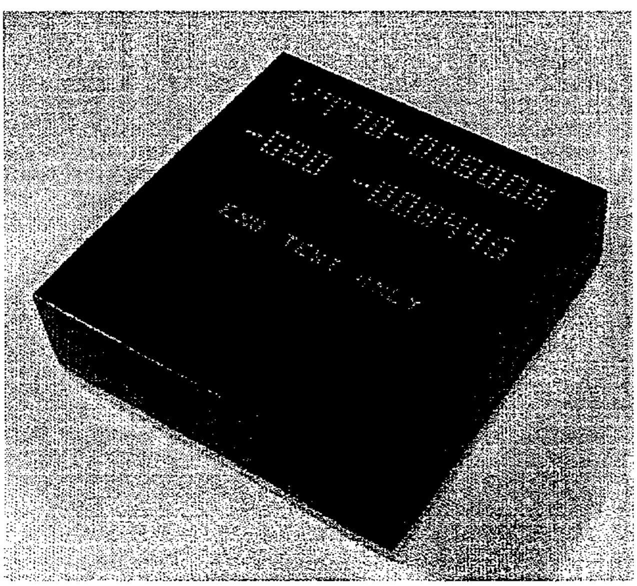
Figure No. 2: Rigid Target Fixture

3.1.3 Ultra High Speed Digital Imaging

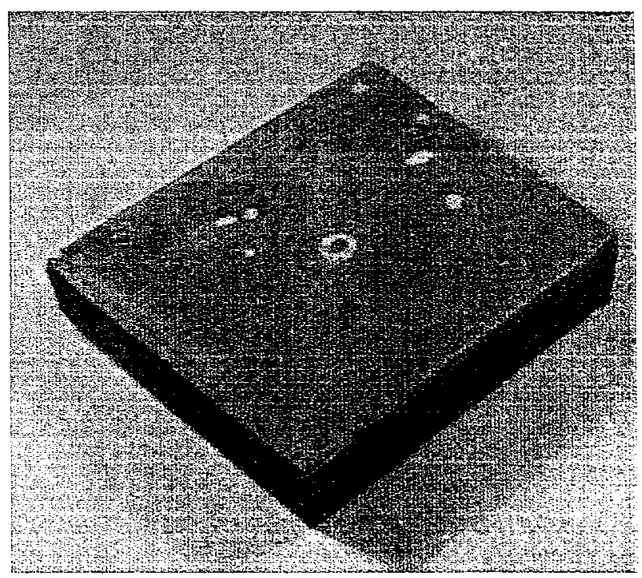
To film the high velocity projectile impacts on the Orbiter HRSI tiles, the Imacon 468 Ultra High Speed Digital imaging system was used. The Imacon 468 employs high-resolution charge couple device (CCD) sensors coupled to a micro channel plate intensifier to acquire short duration exposures of high-speed events. This system provides eight (8) separate images of the event and can have exposure times as short as 10 ns, which is equivalent to a frame rate of 100 million frames-per-second. Test images are immediately available for review after each test. Filming the impacts provided information about the integrity and orientation of the projectile before, position of the selected feature, the velocity of the object along the calibrated shot line is calculated.

3.2 Tile Target

A total of 18 engineering tiles and 37 used flight tiles, shown in Figure No. 4, were tested in this study. The tiles were LI-900 HRSI (9 pounds per cubic inch) as flown on the underside of the Orbiter. A mixture of both engineering and flight tiles were tested under similar conditions to evaluate the conditions of aging on the impact behavior and failure mechanisms. Most of the tiles tested measured 6" x 6" x 2". A select few were slightly thinner with a thickness of approximately 1.5". The tiles were impacted on the exterior or 6" x 6" coated face. Typically, each tile was used for two tests, one impact on each half of the tile face provided that damage did not interfere with the other test. If the tile was not damaged in a test it was reused in the next test. Pretest tile damage such as cracking, voids, and repaired areas was recorded on the data record sheets. Pretest damage areas were avoided, when possible, by carefully selecting the impact location on the tile.



(A) Engineering Tile



(B) Flight Tile

Figure No. 4

during, and after impact. The tile targets response to the impact can also be monitored. Triggering of the camera was accomplished using a high voltage make circuit system mounted at the end of the barrels. As the projectile reaches the end of the gun barrel, a tiny braided wire is pushed up against the inside of the barrel. This completes the circuit, which triggers the camera. The tiny make-wire left a very shallow groove in the projectiles but did not interfere with the flight of the projectile. The digital images were also used to measure the projectile velocity (described in Section 3.1.4). Figure No. 3 is a diagram showing the camera system layout.

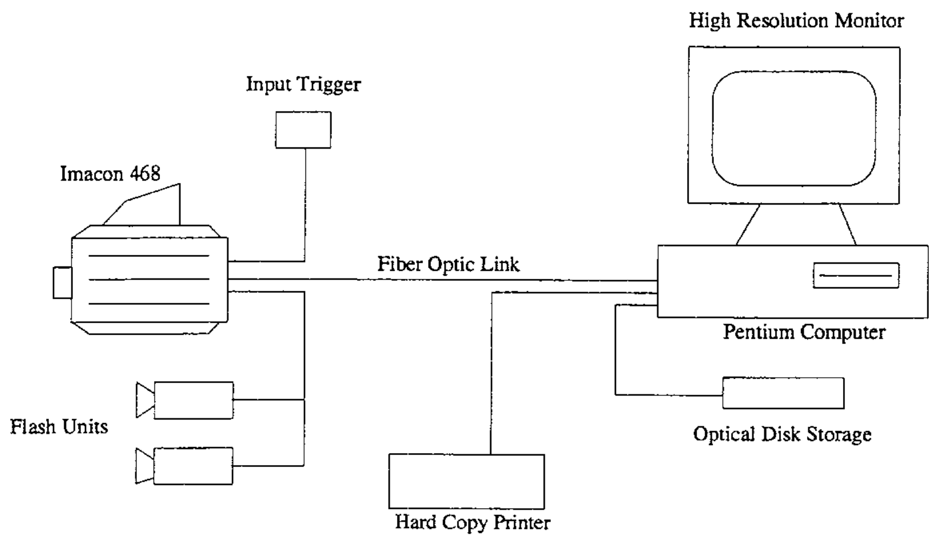


Figure No. 3: Ultra High Speed Imacon 468 Digital Camera System

3.1.4 Velocity Measurement

Projectile velocity was measured using the built-in features of the Imacon 468 Ultra High Speed Digital Imaging System. A part of the camera pretest setup procedure includes performing a dimensional calibration of the shot line in the field of view. After recording a test, the Imacon analysis software allows the user to select, with a crosshair cursor, the location of a unique feature of the projectile (i.e. the leading edge). This unique feature is selected in any two of the eight images. Since the delay time of the image is automatically recorded, as is the change in

3.3 Foam Projectiles

All foam projectiles were NCFI 24-124 samples machined from production sprays performed per requirements below:

- Booth Temperature 103°F±2°F
- Booth Humidity 10%±2%
- Substrate Temperature 125°F±5°F
- Output 25.6 lbs/min/gun
- Hoist Velocity 14.46 inch/min
- RPM/Gun Angle/Clocking/Other parameters standard I/T (with NDS/TPV)

Lockheed Martin supplied six (6) different shapes/sizes of projectiles for this study. The projectiles are listed below and are displayed in Figure No. 5.

[Height x Width x Length]

(1) 0.89" x 0.89" x 0.25" (Originally 1" diameter x ¼" long cylinders)

(2) 1" x 1" x 1" rectangular solids

(3) 1" x 1" x 3" rectangular solids

(4) 3" x 1" x 6" rectangular solids (Later eliminated from the Test Matrix)

(5) 3/8" diameter x 1" long cylinders

(6) 3/8" diameter x 3" long cylinders

The approximate mass of each foam projectile type is as follows:

Projectile Type	**Mass (g)**
0.89" x 0.89' x 0.25"	0.11
1" x 1" x 1"	0.64
1" x 1" x 3"	1.77
1" x 3" x 6" (Eliminated from the Test Matrix)	
3/8" dia. x 1"	0.08
3/8" dia. x 3"	0.23

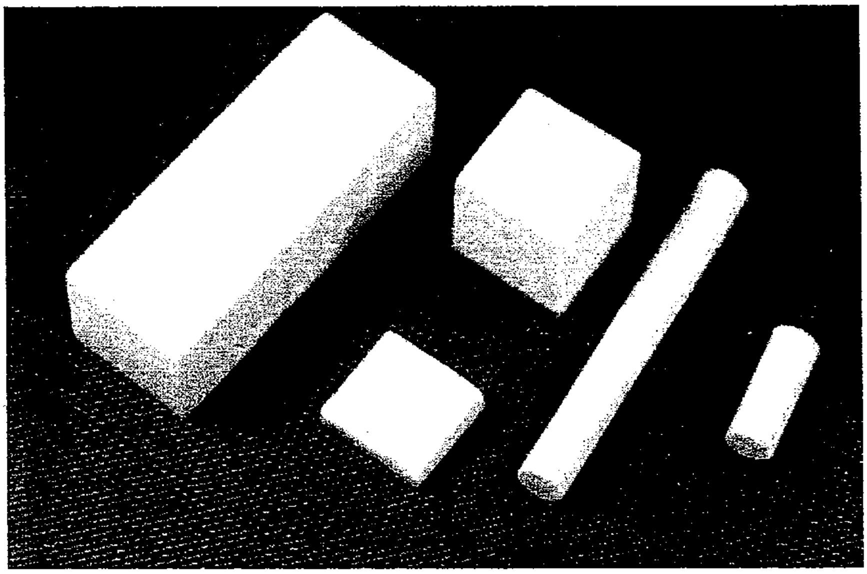


Figure No. 5: Foam Projectiles

Originally, a projectile measuring 1.0" diameter x 0.25" length was to be used in this study. Because of its small length-to-diameter ratio, a sabot was needed to launch the projectile. However, upon separation of the sabot and projectile, the fragile projectile was fracturing. Due to the difficulty of launching the round projectile, the dimensions were changed to 0.89" x 0.89" x 0.25". The square projectile could be launched without a sabot, while retaining the same volume and mass as the previous selection. Tests with the 1.0" x 3.0" x 6.0" projectile were eliminated from the test matrix. The choice to eliminate this projectile was made by the sponsor, due to the establishment of a tile damage threshold early in the program with smaller projectiles.

3.4 Data Recording

Test data was recorded on a standardized data sheet as shown in Figure No. 6. The data sheet contains the following information: test number, date, time, weather conditions, test personnel, orbiter tile type and condition, impact angle, projectile type and weight, gun pressures, measured velocity, damage assessment, and an area to discuss test results. Both digital and 35 mm pictures were taken of the damaged targets. Any pretest defects in the tiles such as cracking was recorded on the data sheets. The Imacon images of each test were also archived for later review.

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Orbiter Tile Impact Testing
SwRI Project No. 06-7503-005

Test No. ______

Date: ________
Time: ________
Conditions: ______________________________
Staff: __________________________________

Target Description:

Serial No. __________
Obliquity (deg.): ______

Projectile Description:

Projectile Dimensions: ______________
Projectile Weight (g): ______
Sabot Weight (g): _____
Total Weight (g): _____

Gun Pressure (psi): P1: ______, P2: ______, P3: ______

Velocity Measurement:

Measurement	Time (us)	Velocity (fps)
1	______	________
2	______	________
	Ave.	________

Tile Damage Assessment:

Crater (Y/N): Length: _____ Width: ______ Depth: ______

Volume: _____ (Weight of Sand _____ x Sand Density ____)

Tile Cracking (Y/N – Describe):

____

____

Comments:

____

____

____

____

Figure No. 6: Data Record Sheet

3.5 Damage Assessment

Tile damage was classified according to the extent of damaged created by the foam projectile. Damage was assessed as being: **No Damage, Cracking of the Coating, Delamination of the Coating, Shallow Crater** (loss of coating), or as a **Crater** (loss of coating and substrate material). Tile damage was assessed by measuring the maximum dimensions (length, width and depth) of the damaged site. If applicable, the volume of the damage (crater) was measured by filling the cavity with fine glass beads of known density. By weighing the volume of glass beads needed to fill the cavity, and knowing the bead specific gravity, the volume of the cavity was calculated.

3.6 Test Matrix

The following tables describe the test matrix for this study. Test Sequence No. 1 is the general test matrix (Table #1). Test Sequence No. 2 is a confirmation of the general matrix (Table #2). Test Sequence No. 3 is a confirmation of prior test results (Table #3). The test matrix tables include information about the **Test Number, Projectile Size, Projectile Velocity**, and **Impact Angle**. The determination of the impact angle (the angle at which the projectile was launched against the tile target) is described in Figure No. 7. Note that a normal impact would be measured as a 90-degree incident angle.

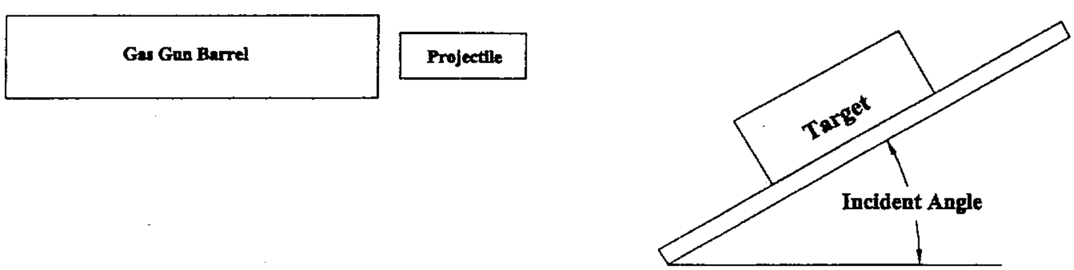


Figure No. 7: Impact Angle Diagram

During the initial stages of this study the decision was made by the sponsor to eliminate all tests with the 1.0” x 3.0” x 6.0” projectile due to the levels of damaged created by the smaller projectiles. The tests that were eliminated include Tests No. 61 through No. 80, No. 87, No. 88, No. 95, and No. 96.

Table No. 1: Sequence No. 1 Test Matrix

Test Number	Velocity (feet/second)	Incident Angle (degrees)	Particle Size (inches)
1	400	10	.89” x .89” x .25” rectangular solid
2	800	10	89” x .89” x .25” rectangular solid
3	1200	10	89” x .89” x .25” rectangular solid
4	1600	10	89” x .89” x .25” rectangular solid
5	400	15	89” x .89” x .25” rectangular solid
6	800	15	89” x .89” x .25” rectangular solid
7	1200	15	89” x .89” x .25” rectangular solid
8	1600	15	89” x .89” x .25” rectangular solid
9	400	23	89” x .89” x .25” rectangular solid
10	800	23	89” x .89” x .25” rectangular solid
11	1200	23	89” x .89” x .25” rectangular solid
12	1600	23	89” x .89” x .25” rectangular solid
13	400	30	89” x .89” x .25” rectangular solid
14	800	30	89” x .89” x .25” rectangular solid
15	1200	30	89” x .89” x .25” rectangular solid
16	1600	30	89” x .89” x .25” rectangular solid
17	400	40	89” x .89” x .25” rectangular solid
18	800	40	89” x .89” x .25” rectangular solid
19	1200	40	89” x .89” x .25” rectangular solid
20	1600	40	89” x .89” x .25” rectangular solid

Test Number	Velocity (feet/second)	Impact Angle (degrees)	Particle Size (inches)
21	400	10	1" x 1" x 1" rectangular solid
22	800	10	1" x 1" x 1" rectangular solid
23	1200	10	1" x 1" x 1" rectangular solid
24	1600	10	1" x 1" x 1" rectangular solid
25	400	15	1" x 1" x 1" rectangular solid
26	800	15	1" x 1" x 1" rectangular solid
27	1200	15	1" x 1" x 1" rectangular solid
28	1600	15	1" x 1" x 1" rectangular solid
29	400	23	1" x 1" x 1" rectangular solid
30	800	23	1" x 1" x 1" rectangular solid
31	1200	23	1" x 1" x 1" rectangular solid
32	1600	23	1" x 1" x 1" rectangular solid
33	400	30	1" x 1" x 1" rectangular solid
34	800	30	1" x 1" x 1" rectangular solid
35	1200	30	1" x 1" x 1" rectangular solid
36	1600	30	1" x 1" x 1" rectangular solid
37	400	40	1" x 1" x 1" rectangular solid
38	800	40	1" x 1" x 1" rectangular solid
39	1200	40	1" x 1" x 1" rectangular solid
40	1600	40	1" x 1" x 1" rectangular solid

Table No. 1 (Cont.)

Test Number	Velocity (feet/second)	Impact Angle (degrees)	Particle Size (inches)
41	400	10	3" x 1" x 1" rectangular solid
42	800	10	3" x 1" x 1" rectangular solid
43	1200	10	3" x 1" x 1" rectangular solid
44	1600	10	3" x 1" x 1" rectangular solid
45	400	15	3" x 1" x 1" rectangular solid
46	800	15	3" x 1" x 1" rectangular solid
47	1200	15	3" x 1" x 1" rectangular solid
48	1600	15	3" x 1" x 1" rectangular solid
49	400	23	3" x 1" x 1" rectangular solid
50	800	23	3" x 1" x 1" rectangular solid
51	1200	23	3" x 1" x 1" rectangular solid
52	1600	23	3" x 1" x 1" rectangular solid
53	400	30	3" x 1" x 1" rectangular solid
54	800	30	3" x 1" x 1" rectangular solid
55	1200	30	3" x 1" x 1" rectangular solid
56	1600	30	3" x 1" x 1" rectangular solid
57	400	40	3" x 1" x 1" rectangular solid
58	800	40	3" x 1" x 1" rectangular solid
59	1200	40	3" x 1" x 1" rectangular solid
60	1600	40	3" x 1" x 1" rectangular solid

Test Number	Velocity (feet/second)	Impact Angle (degrees)	Particle Size (inches)
61	400	10	6" x 3" x 1" rectangular solid
62	800	10	6" x 3" x 1" rectangular solid
63	1200	10	6" x 3" x 1" rectangular solid
64	1600	10	6" x 3" x 1" rectangular solid
65	400	15	6" x 3" x 1" rectangular solid
66	800	15	6" x 3" x 1" rectangular solid
67	1200	15	6" x 3" x 1" rectangular solid
68	1600	15	6" x 3" x 1" rectangular solid
69	400	23	6" x 3" x 1" rectangular solid
70	800	23	6" x 3" x 1" rectangular solid
71	1200	23	6" x 3" x 1" rectangular solid
72	1600	23	6" x 3" x 1" rectangular solid
73	400	30	6" x 3" x 1" rectangular solid
74	800	30	6" x 3" x 1" rectangular solid
75	1200	30	6" x 3" x 1" rectangular solid
76	1600	30	6" x 3" x 1" rectangular solid
77	400	40	6" x 3" x 1" rectangular solid
78	800	40	6" x 3" x 1" rectangular solid
79	1200	40	6" x 3" x 1" rectangular solid
80	1600	40	6" x 3" x 1" rectangular solid

Table #2: Sequence No. 2 Test Matrix

Test Number	Velocity (feet/second)	Impact Angle (degrees)	Particle Size (inches)
81	800	10	1" dia. x ¼" long cylinder
82	1600	10	1" dia. x ¼" long cylinder
83	800	10	1" x 1" x 1" rectangular solid
84	1600	10	1" x 1" x 1" rectangular solid
85	800	10	3" x 1" x 1" rectangular solid
86	1600	10	3" x 1" x 1" rectangular solid
87	800	10	6" x 3" x 1" rectangular solid
88	1600	10	6" x 3" x 1" rectangular solid
89	800	23	1" dia. x ¼" long cylinder
90	1600	23	1" dia. x ¼" long cylinder
91	800	23	1" x 1" x 1" rectangular solid
92	1600	23	1" x 1" x 1" rectangular solid
93	800	23	3" x 1" x 1" rectangular solid
94	1600	23	3" x 1" x 1" rectangular solid
95	800	23	6" x 3" x 1" rectangular solid
96	1600	23	6" x 3" x 1" rectangular solid

Table #3: Sequence No. 3 Test Matrix

Test Number	Velocity (feet/second)	Impact Angle (degrees)	Particle Size (inches)
97	1009	60	3/8" diam. x 1" long cylinder
98	1620	30	3/8" diam. x 1" long cylinder
99	735	60	3/8" diam. x 1" long cylinder
100	960	30	3/8" diam. x 1" long cylinder
101	1206	30	3/8" diam. x 3" long cylinder
102	1181	30	3/8" diam. x 3" long cylinder
103	1025	30	3/8" diam. x 3" long cylinder
104	1200	60	3/8" diam. x 3" long cylinder

4.0 Test Results

In the following section the results of the Orbiter tile impact study are presented. A limited analysis and discussion of the results are provided in this report. Further assessment of the enclosed impact test data and application of these results to the Orbiter tile damage issue will be performed by the NASA and it's supporting contractors.

The orbiter tile impact test results have been grouped in tables according to projectile type. Tables No. 4, No. 5, No. 6, and No. 7 contain the results for the .89" x .89" x .25", 3/8" dia. x 1.0" and 3/8" dia. x 3.0", 1.0" x 1.0" x 1.0", and the 1.0" x 1.0" x 3.0" projectile tests, respectively. Each table includes the following information: **Test Number, Measured Projectile Velocity, Impact Angle, Damage to the Tile (Yes or No), Damage Description, Damage Volume Measurement,** and **Comments.**

Graphical representations of the tile impact test results are provided in Figures No. 8, No. 9, and No. 10. In all three plots, kinetic energy [1/2 mass x $(\text{velocity})^2$] is used to describe the foam projectile. The shape of the foam projectiles is not taken into consideration. All data points in each plot are color coded according to the incidence angle at which the projectile impacted the tile target.

Figure No. 8 is a plot of the resulting tile damage level or category (1 – No Damage, 2 – Cracking and Delamination of the Coating, 3 – Shallow Crater, 4 – Crater) as a function of the foam projectile kinetic energy. The plot shows a general trend where the level of damage (category) increases as kinetic energy and/or incidence angle are increased. As the incidence angle reaches 60 degrees, projectiles with relatively low kinetic energy (3/8" diameter projectile in this case) can inflict high levels of damage on the tile target.

Figure No. 9 is a plot of maximum crater depth as a function of projectile kinetic energy. In general, as the incidence angle of impact is increased, crater depth increases. For a given incidence angle, crater depth increases as kinetic energy increases.

Figure No. 10 is a plot of crater volume as function of projectile kinetic energy. In general, crater volume increases as the incidence angle and/or kinetic energy are increased. As expected, tests conducted with large fast moving projectiles fired at increased incidence angles produced the largest crater volumes. Note that in several tests, the crater extended to the edge of the tile target. Thus the total possible crater volume could not be determined. Such tests are labeled with a "**" symbol in the damage dimension column of the results tables. The data point for Test No. 60 in which the 1" x 1" x 3" projectile was launched at a 40 degree angle at 1432 fps is not included in the plot of Figure No. 10. The damage was too extensive to accurately measure volume.

In the plots shown in Figures No. 8, No. 9, and No. 10 there is a degree of mixed results where definite conclusions are difficult to make. The cause of the mixed results in the plots is mainly attributed to the grouping together of the data from the various shaped projectiles and due to the inherent randomness in the penetration/failure events in brittle or soft targets.

Table No. 4: Test Results for the .89" x .89" x .25" Projectile

Test No.	Velocity (fps)	Impact Angle (degrees)	Damage (Yes or No)	Damage Type	Damage Max. Dimensions (Length x Wide x Depth)	Comments	Damage Volume (cubic inches)
1	441	10	No	*****	*****	Velocity (+41 fps)	*****
2	975	10	No	*****	*****	Velocity (+175 fps)	*****
3	1166	10	No	*****	*****	Velocity (-34 fps)	*****
4 (B)	1550	10	No	*****	*****	Velocity (-50 fps)	*****
5	731	15	No	*****	*****	Velocity (+331 fps)	*****
6	952	15	No	*****	*****	Velocity (+152 fps)	*****
7	1279	15	No	*****	*****	Velocity (+79 fps)	*****
8	1606	15	Yes	Delamination and Cracking of Coating	1.0" Diameter	Velocity (+6 fps),	0.02
9	579	23	No	*****	*****	Velocity (+179 fps)	*****
10	794	23	No	*****	*****	Velocity (-6 fps)	*****
11	1257	23	Yes	Delamination and Cracking of Coating	0.94" Diameter	Velocity (+57 fps)	*****
12	1490	23	Yes	Delam., Cracking, Loss of Coating	1.25" Diameter	Velocity (-110 fps)	0.04
13	552	30	No	*****	*****	Velocity (+152 fps)	*****
14	825	30	No	*****	*****	Velocity (+25 fps)	*****
15 (A)	1160	30	Yes	Shallow Crater, Loss of Coating	0.94 x 1.25" x 0.13"	Velocity (-40 fps)	0.03
16 (B)	1605	30	Yes	Crater	1.34" x 1.1" x 0.26"	Velocity (+5 fps)	0.13
17	516	40	No	*****	*****	Velocity (+116 fps)	*****
18	799	40	Yes	Delamination and Cracking of Coating	0.66" x 0.98"	Velocity (-1 fps)	*****
19 (D)	1252	40	Yes	Crater	1.0" x 1.1" x 0.41"	Velocity (+52 fps)	0.19
20 (F)	1520	40	Yes	Crater	1.44" x 1.2" x 0.47"	Velocity (-80 fps)	0.24
81	750	10	No	*****	*****	Velocity (-50 fps)	*****
82	1553	10	No	*****	*****	Velocity (-47 fps)	*****
89	785	23	No	*****	*****	Velocity (-15 fps)	*****
90 (B)	1640	23	Yes	Shallow Crater, Loss of Coating	1.1" x 1.15" x 0.11"	Velocity (+40 fps)	0.03

Table No. 5: Test Results for the 3/8" Diameter Projectiles

Test No.	Projectile Length	Velocity (fps)	Impact Angle (degrees)	Damage (Yes or No)	Damage Type	Damage Max. Dimensions (Length x Wide x Depth)	Comments	Damage Volume (cubic inches)
97	1.0"	1000	60	Yes	Crater	0.53" dia. X 0.35" deep	Velocity (-9 fps), This is the New Test 97	0.05
98 (A)	1.0"	1692	30	Yes	Crater	1.07" x 0.56" x 0.36"	Velocity (+72 fps), New Test 98A	0.10
99 (B)	1.0"	730	60	Yes	Crater	0.62" dia. x 0.15" deep	Velocity (-5 fps), This is the New Test 99B	0.02
100	1.0"	929	30	No	*****	*****	Test No. 97 in NoteBook, Vel (-31 fps)	*****
101 (B)	3.0"	1317	30	Yes	Crater	1.85" x 1.08" x 0.5"	Velocity (+111 fps), New Test 101B	0.18
102	3.0"	1317	30	Yes	Crater	1.85" x 1.08" x 0.5"	Velocity (+111 fps), New Test 101B	0.18
103	3.0"	1071	30	Yes	Crater	1.5" x 1.0" x 0.5"	Velocity (+46 fps), New Test 103	0.17
104	3.0"	1250	60	Yes	Crater	1.01" dia. X 0.9" deep	Velocity (+50 fps), New Test 104, Proj. Slightly Broekn Up	0.15

Table No. 6: Test Results for the 1.0" x 1.0" x 1.0" Projectile

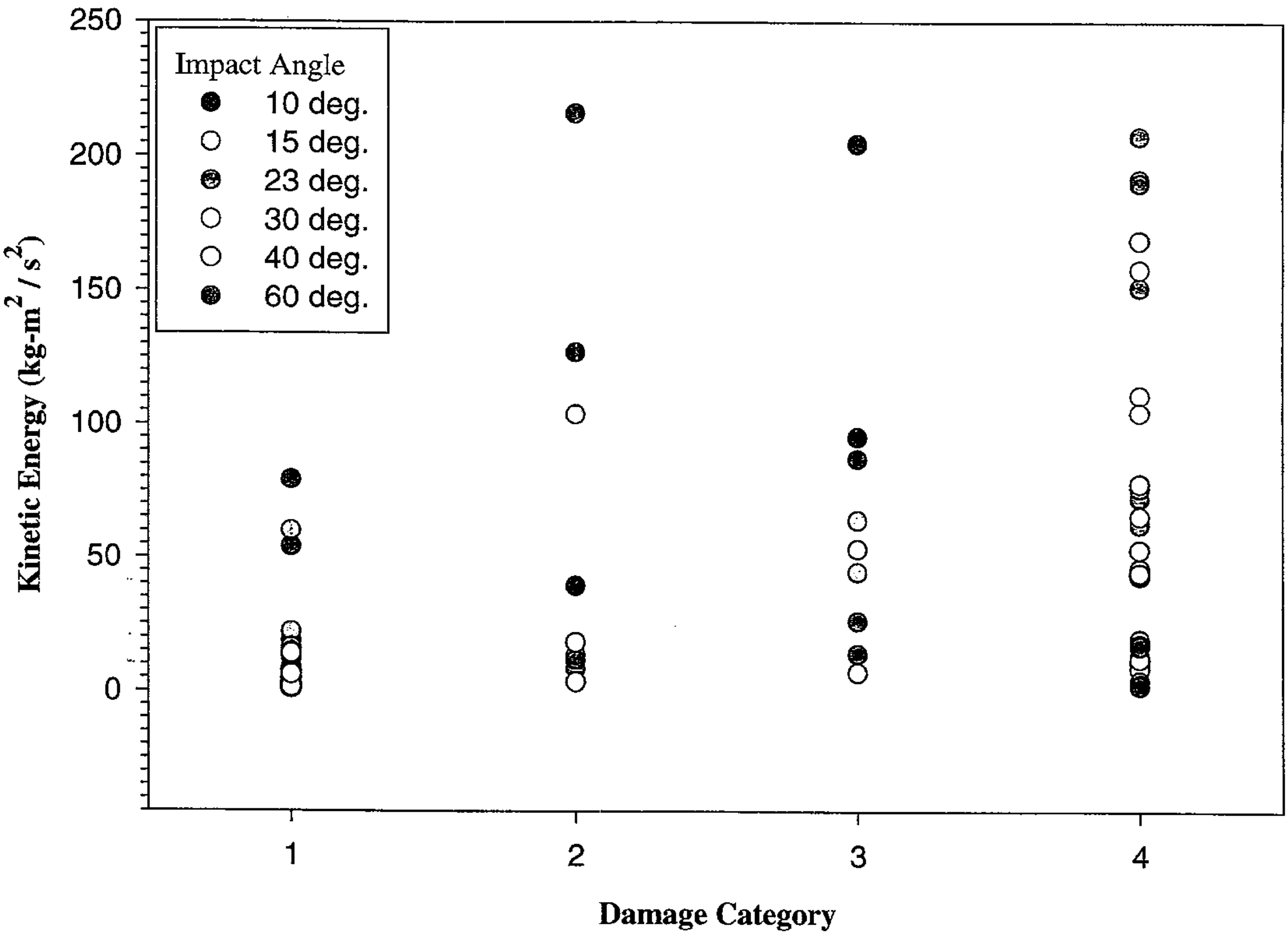
Test No.	Velocity (fps)	Impact Angle (degrees)	Damage (Yes or No)	Damage Type	Damage Max. Dimensions (Length x Wide x Depth)	Comments	Damage Volume (cubic inches)
21	338	10	No	*****	*****	Velocity (-62 fps)	*****
22	670	10	No	*****	*****	Velocity (-130 fps)	*****
23	1147	10	Yes	Coating Cracking	one small crack	Velocity (-53 fps)	*****
24 (F)	1788	10	Yes	Shallow Crater, loss of Coating	2.0" x 2.5" x 0.1"	Velocity (+188 fps)	0.11
25	490	15	No	*****	*****	Velocity (+90 fps)	*****
26 (A)	856	15	No	*****	*****	Velocity (+56 fps)	*****
27	1221	15	Yes	Shallow Crater, loss of Coating	1.25" x 2.5" x 0.1"	Velocity (+21 fps)	0.11
28 (B)	1465	15	Yes	Shallow Crater, loss of Coating	2.0" x 2.0" x 0.1"	Velocity (-135 fps), Projectile Slightly Broken Up	0.10
29	353	23	No	*****	*****	Velocity (-47 fps)	*****
30 (B)	934	23	Yes	Shallow Crater, loss of Coating	1.0" x 2.0" x 0.1"	Velocity (+134 fps)	0.05
31	1233	23	Yes	Crater	**1.25" x 2.25" x 0.25"	Velocity (+33 fps), Extended to Tile Edge	0.34
32	1557	23	Yes	Crater	3.75" x 1.5" x 0.4"	Velocity (-43 fps)	0.64
33	452	30	No	*****	*****	Velocity (+52 fps)	*****
34 (A)	805	30	Yes	Crater	2.0" x 1.25" x 0.25"	Velocity (+5 fps)	0.13
35	1240	30	Yes	Crater	2.25" x 1.38" x 0.4"	Velocity (+40 fps), Projectile Cracked	0.47
36 (A)	1483	30	Yes	Crater	2.5" x 1.5' x 0.5"	Velocity (-117 fps), Projectile Slightly Broken Up	0.58
37	447	40	No	*****	*****	Velocity (+47 fps)	*****
38	767	40	Yes	Crater	1.5" x 1.25" x 0.38"	Velocity (-33 fps), Projectile lost a small piece	0.21
39	1216	40	Yes	Crater	2.5" x 1.1" x 0.5"	Velocity (+16 fps)	0.65
40 (A)	1616	40	Yes	Crater	3.0" x 1.5" x 0.5"	Velocity (+16 fps), Projectile Slightly Broken Up	0.61
83	790	10	No	*****	*****	Velocity (-10 fps)	*****
84 (B)	1710	10	Yes	Shallow Crater, loss of Coating	**2.25" x 1.63" x 0.10"	Velocity (+110), Extended to Tile Edge	0.08
91	794	23	Yes	Crater	1.7" x 1.21" x 0.24"	Velocity (-6 fps)	0.17
92	1596	23	Yes	Crater	3.35" x 1.4" x 0.40"	Vel. (-4 fps), Proj. Slightly Broken Up	0.67

** Crater Extended to Tile Edge

Table No. 7: Test Results for the 1.0" x 1.0" x 3.0" Projectile

Test No.	Velocity (fps)	Impact Angle (degrees)	Damage (Yes or No)	Damage Type	Damage Max. Dimensions (Length x Wide x Depth)	Comments	Damage Volume (cubic inches)
41	409	10	No	*****	*****	Velocity (+9 fps)	*****
42	809	10	No	*****	*****	Velocity (+9 fps)	*****
43	1242	10	Yes	Very Slight Cracking at Impact site	*****	Velocity (+42 fps)	*****
44	1620	10	Yes	Very Slight Cracking at Tile edge	*****	Velocity (+20 fps),Projectile Slightly Broken Up	*****
45	399	15	No	*****	*****	Velocity (- 1 fps)	*****
46	853	15	No	*****	*****	Velocity (+53 fps)	*****
47 (A)	1122	15	Yes	Delamination and Cracking of Coating	1.5" x 1.0"	Velocity (-78 fps)	*****
48 (C)	1526	15	Yes	Crater	**3.35" x 1.25" x 0.5"	Velocity (-74 fps),Extended to Tile Edge	0.86
49	440	23	No	*****	*****	Velocity (+40 fps)	*****
50 (A)	723	23	Yes	Crater	1.8" x 1.1" x 0.2"	Velocity (-67 fps)	0.29
51 (B)	1356	23	Yes	Crater	**4.25" x 1.3" x 0.63"	Velocity (+156 fps), Extended to Tile Edge	2.51
52 (B)	1588	23	Yes	Crater	**4.0" x 1.1" x 0.8"	Velocity (-12 fps), Extended to Tile Edge	2.59
53	410	30	No	*****	*****	Velocity (+10 fps)	*****
54	803	30	Yes	Shallow Crater, Loss of Coating	2.0" x 1.25" x 0.08"	Velocity (+3 fps)	0.17
55	1161	30	Yes	Crater	**3.65" x 1.5" x .75"	Velocity (-39 fps), Extended to Tile Edge	2.01
56	1386	30	Yes	Crater	4.13" x 2.75" x 0.6"	Velocity (-214 fps),Projectile Slightly Broken Up	1.83
57 (A)	467	40	Yes	Delamination and Cracking of Coating	0.75" diameter x 0.13" deep	Velocity (+67 fps)	0.01
58	801	40	Yes	Crater	2.5" x 1.2" x 0.4"	Velocity (+1 fps)	0.76
59 (A)	1126	40	Yes	Crater	4.5" x 2.0" x 1.0"	Velocity (-74 fps)	2.30
60	1432	40	Yes	Crater	**6.0" x 3.0" x 2.0"	Velocity (-168 fps), Projectile Broke Up	Unmeasurable
85	980	10	No	*****	*****	Velocity (+180 fps)	*****
86	1577	10	Yes	Shallow Crater, Loss of Coating	**2.56" x 1.7" x 0.11"	Velocity (-23 fps)	0.13
93	870	23	Yes	Crater	2.25" x 1.32" x 0.27"	Velocity (+70 fps)	0.37
94 (A)	1520	23	Yes	Crater	**5.02" x 1.61" x 0.65"	Velocity (-80 fps), Slightly Cracked Proj.	2.02

** Crater Extended to Tile Edge



(1-No Damage, 2-Cracking and Delamination of Coating, 3-Shallow Crater, 4-Crater)

Figure No. 8: Projectile Kinetic Energy vs. Damage Category

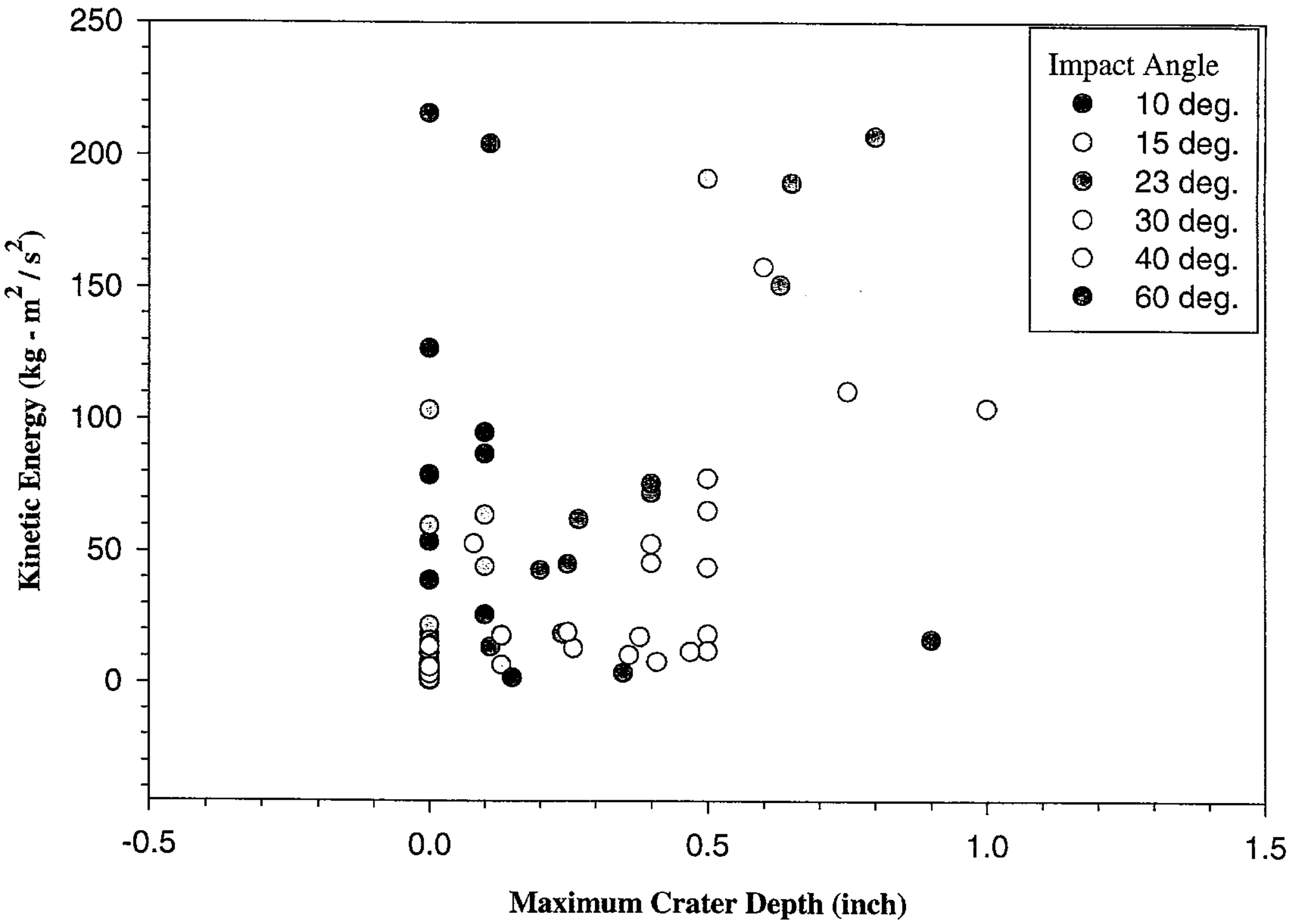


Figure No. 9: Projectile Kinetic Energy vs. Max. Crater Depth

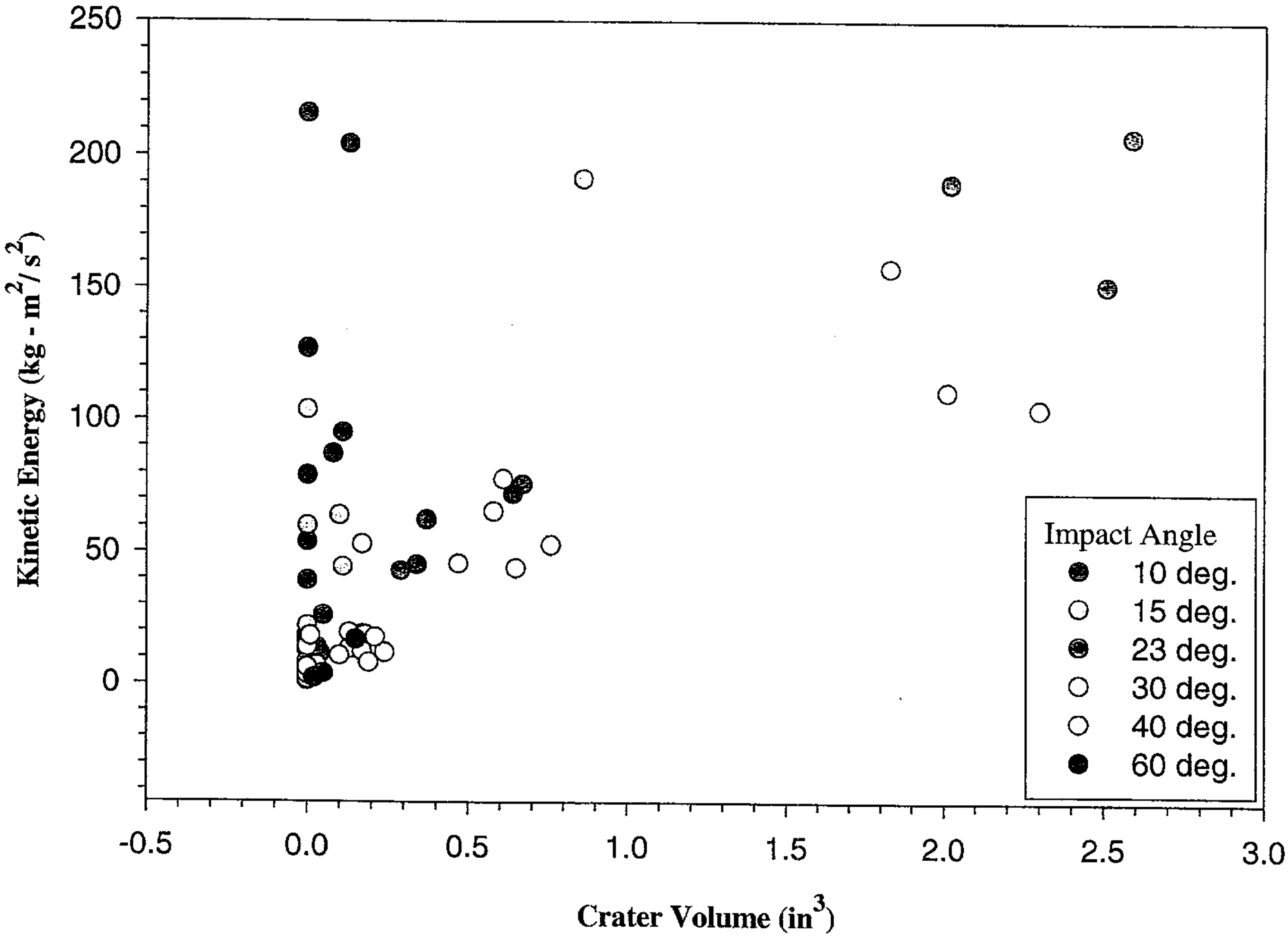


Figure No. 10: Projectile Kinetic Energy vs. Crater Volume

Photographic records of the damaged tiles are given in Appendix A. On most tiles, multiple tests were conducted. The test number for a given damage site has been written above or below the damage site. Figure No. 11 is an example of an impacted tile with test number labeling. Data Record Sheets for each test are given in Appendix B.

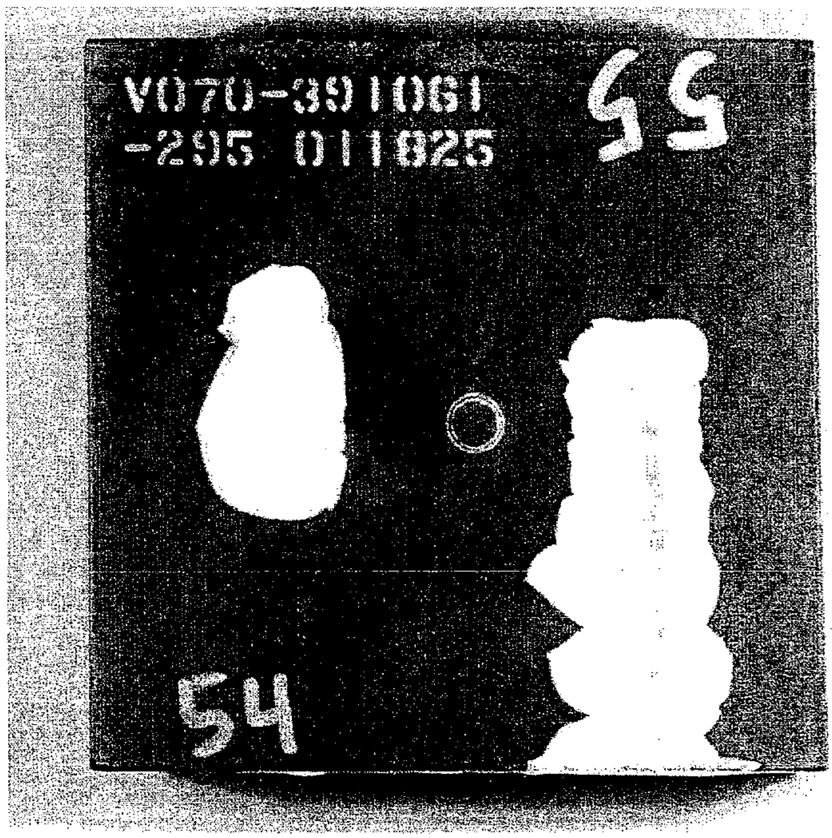


Figure No. 11: Photograph of damaged tile

During the performance of certain tests, circumstances occurred that required the test to be repeated. Reasons for repeating a test included too slow or too fast projectile velocity, no velocity reading due to a malfunction of the trigger for the Imacon Imaging System, or damage to the projectile during launch. If tile damage was sustained during a test in which something like this occurred, the results were recorded and the test repeated. Each subsequent test was given a letter suffix (i.e.: Test No. 40A). Thus, if several attempts were required to meet the criteria of a specific test, the last test would be the official test. When a velocity reading could not be measured, an estimated velocity based on the database of velocities was recorded. The estimated velocity values are considered to be fairly accurate since the chamber pressure of the gun was known and the system is very repeatable. A table describing all the tests conducted (131 total tests) is given in Appendix C. An asterisk has been placed by the official test number in the combined result table.

The Imacon images recorded for each test are provided in Appendix D. All valid Imacon records are given with all eight images printed on a single page. An example set of the eight Imacon images, expanded to full-page size, has been provided for each projectile type in Appendix E. The eight full size Imacon images of a 1" x 1" x 3" projectile breaking up before impact are also given (Test No. 60).

Per the sponsor's request, two additional tests (Tufi-1 and Tufi-2) were conducted on a different type of thermal protection tile known as the Toughened Unipiece Fiberous Insulation or TUFI tile. The results of these two tests are also included in the combined test results table in Appendix C.

Section 5.0: Conclusions

In this program the effects of impacting Orbiter HRSI tiles with NCFI 24-124 foam projectiles, launched at various incidence angles and velocities, were successfully studied. The damage capability of the foam projectiles was determined. From these test results, comparisons to previously conducted

0tests can be made.

All scheduled tests were completed for each of the projectile types as described in the test matrix. The series of tests with the large 1" x 3" x 6" foam projectiles was eliminated due to the establishment of a tile damage threshold early in the program with smaller projectiles.

The use of the ultra high speed Imacon 468 digital camera proved to be a very valuable aid in diagnosing the experiments. The digital camera was used to measure the velocity of the projectile as well as provide visual evidence of the pre-impact integrity of the fragile foam projectiles. Visual analysis of the foam projectile impacting the tile target was also possible with the Imacon camera.

The last important remark that should be made addresses the use of the compressed gas gun for launching the fragile foam projectiles. Preliminary testing proved that the best method of launching the various size foam projectiles was to use custom barrels that were designed with bores that dimensionally match the cross section of the projectile. A projectile that fits in the custom barrel properly eliminates the need for a sabot carrier. The difficulty with using a sabot lies in the removal of the sabot prior to the foam impacting the target. It was almost impossible to reach high velocities and not fracture the fragile foam projectile or launch some part of the sabot. With such a lightweight projectile, sabot pieces can cause more severe damage than the foam. All projectile types in the study were successfully launched without the use of a sabot. However, as testing velocities reached 1600 fps, some projectiles began to break up due to the fragile nature of the foam material.